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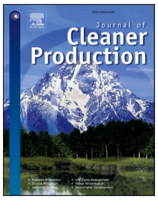

Review

# Decision support tools of sustainability assessment for urban stormwater management – A review of their roles in governance and management

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ABSTRACT

Urban areas face growing sustainable challenges arising from stormwater issues, necessitating the evolution of stormwater management concept and practice. This transformation not only entails the adoption of a multifunctional, holistic, and sustainable approach but also involves the integration of water quality and quantity considerations with governance and management aspects. A means to do so is via decision support tools. However, whilst existing studies using the tools by employing sustainability assessment principles or as indicators to plan blue-green infrastructures and strategies, uncertainties remain regarding how decision support tools encompass governance and management dimensions. The aim of this review study is to provide much-needed clarity on this aspect, in doing so, a systematic review of decision support tools used in sustainability assessment within the stormwater management context is conducted, focusing on their abilities to include governance and management. Findings encompass governance aspects, such as actors, discourses, rules, and resources considered, and explore how these relate to long-term management. The results reveal the recognized potential of decision support tools in facilitating governance and management for sustainable stormwater management, however, future research and efforts need to be allocated in: (i) Exploring practical challenges in integrating all sustainability assessment pillars with consistent criteria into decision support tools, to determine the optimal use of all criteria in fostering open and informed stormwater governance and management. (ii) Understanding how to engage diverse stormwater actors with future decision support tools, to secure ownership and relevance. (iii) Using retrospective (ex-post) sustainability assessments to provide more tangible knowledge and to support long-term management.

## 1. Introduction

### 1.1. Sustainable stormwater management

The concept of sustainable development is at the core of urban stormwater management (SWM) by designating that this task is not exclusively underscoring the traditional engineering approach of runoff retention, conveyance, flood control, and quality treatment. Rather, SWM is increasingly considered a holistic and integrated approach to complex urban challenges. As such, SWM addresses environmental concerns of ecological, socio-technological, and social-economical magnitudes where technical means to abate flooding, stormwater discharges, and pollution control are integrated into a wider and comprehensive sustainable context and adopted as sustainable SWM (Flynn and Traver, 2013; Mell and Clement, 2020; Porse, 2013). Such demands are creating an ever-challenging task, as the already complicated existing hyetographic, topographic, hydrological, and engineering information for stormwater control, needs to be added with quantitative and qualitative data from technological, social, environmental, and economic perspectives to be fully acknowledged as sustainable SWM (Depietri and McPhearson, 2017; Makropoulos et al., 2008).

To comprehend such complexities, several concepts have been developed over the past decades, *e.g.*, Water Sensitive Urban Design (Wong, 2006), Low Impact Development (USEPA, 2000), and Sustainable Urban Drainage Systems (Fletcher et al., 2015). These concepts have been ascribed not only to mitigate pluvial flooding and water quality treatment but also to support heat mitigation, biodiversity, health, recreation, *etc.* (Cettner et al., 2014). As such, these concepts are to varying degrees including nature processes in the development of specific measures to tackle stormwater, such as Nature-based Solutions

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(NbS), which is still perceived as having a broad view of nature, and an emphasis on participatory processes in the creation and management (Sowińska-Świerkosz and García, 2022).

### 1.2. Challenges in stormwater governance and management

Sustainable SWM needs collective actions and cannot be achieved within existing governance structures. At least within industrialized countries, governance generically refers to the process of decision-making by which society defines and handles its pressing concerns (Iribarnegaray and Seghezzo, 2012; Jansson et al., 2018; van Zeijl-Rozema et al., 2008). The notion of governance in sustainable SWM is gaining more and more attention in the EU, from the embedded concept in the supranational regulation such as the European Water Framework Directive (Todo and Sato, 2002), and to the governance modes per se in national sustainable SWM practices such as the urban decentralized management in Sweden and Germany (Bohman et al., 2020; Geyler et al., 2019)

Governance arrangements or policy arrangements have been defined to comprise both resources and actors whose roles and relations define the outcome of a planning or management decision (Arnouts and Arts, 2012). A wider understanding of a policy arrangement as a conceptual framework was developed in environmental policy studies to assist the understanding of the content and organization of a given policy domain, namely, the policy arrangement model (Arts et al., 2006). The model can be used to describe the state in which the interaction between actors, discourses, resources and rules of the game solidifies in a temporary stable structure before socio-environmental changes force them to readjust their interdependency (Qiao et al., 2019). Management of stormwater comprises multi-actor processes between the local government and the public, by which decisions are developed and communicated. Such initiatives may come from the government itself but are also sometimes driven by an increasing demand from the public to participate (Münster et al., 2017). Thus, while the traditional and conventional piped drainage systems mainly was organized and managed within one department (*e.g.,* the water department), sustainable SWM need to be aligned with more complex governance structures, including decentralized management by cooperation across a variety of departments, *e.g.*, water, planning, parks, and environmental departments, as well as involving a multitude of actors from outside the government organization (Qiao et al., 2019). This governance approach further epitomizes how sustainable SWM is neither a single discipline nor a sole proposition that can provide comprehensive and sustainable solutions.

### 1.3. Decision support tools for sustainability assessment of stormwater management

To address complex decision-making processes, various Decision Support Tools (DSTs) have been developed for the sustainability assessment of urban SWM. Such tools can aid decision-makers to evaluate the potential impacts of different stormwater control measures or management strategies on the environment, technology, economy, and society, to elicit trade-offs and opportunities for improvement (George, 1999; Gibson et al., 2005). Additionally, it can provide a framework for integrating sustainability considerations into the decision-making process and for measuring progress over time (Sheate, 2011). Unlike other assessment approaches, such as risk assessment, that analyze the potential disaster or events (Duan et al., 2022), sustainability assessment is derived from the domain of impact assessment, capturing a decision-making process of identifying, measuring, and evaluating the potential impacts of alternatives against the sustainability domains of economy, environment, technology, and social aspects (Devuyst, 2000; Gibson, 2006; Hacking and Guthrie, 2008; Millennium ecosystem assessment, 2005).

Sustainability assessment is also considered one of the most intricate assessment approaches, as it not only entails any discipline underpinned by the concept of sustainability but can also be applied in all levels of decision-making from projects to strategic policies, plans, and programs. Moreover, it can be formal or informal, legally prescribed, voluntarily applied, policy-driven, or science-driven (Pope and Grace, 2006; Sala et al., 2015). The richness, fuzziness, and complexity of sustainability are becoming an open concept that allows different interpretations dependent on the user's perception, background, knowledge, and experience (Pope et al., 2017). For example, Bixler et al. (2020) developed a dynamic assessment framework for green infrastructure, while Castro (2022) introduced a system thinking framework for environmental policymaking. Denjean et al. (2017) proposed an NbS framework emphasizing insurance value, and Ghafourian et al. (2021) established an economic assessment framework for NbS in circular water.

While existing sustainability assessment studies conform fundamentally by utilizing sustainability principles (pillars hereinafter) as indicators to explore optimal stormwater control measures and sustainable SWM strategies with DSTs, extensive reviews and comparative studies (Jayasooriya and Ng, 2014; Kumar et al., 2021; Qureshi and Rachid, 2021) have scrutinized input parameters, resultant data, strengths, applicability, performance, and limitations of DSTs. However, despite this extensive exploration, the extent to which DSTs in sustainability assessment incorporate dimensions to support governance and management in the decision-making process for sustainable SWM remains unclear.

With this review, we aim to understand how DSTs can support decision-making for holistic and integrated governance and management of sustainable SWM. To drive the review process, we have formulated the following three objectives:

> Objective 1: How are decision support tools used in sustainability assessment of stormwater management?
> Objective 2: What stormwater management themes are decision support tools applied for?
> Objective 3: How do existing decision support tools assist sustainable stormwater governance and management perspectives based on the policy arrangement model?

## 2. Methods

We conducted a systematic review (Grant and Booth, 2009), and followed the PRISMA approach (Fig. 1.) to extract our findings (Page et al., 2021). Using the search engines Web of Science (Core), Scopus, and EBSCOhost we followed an iterative process of search strings under the category of "title-abstract-keywords". We grouped our search into three main strands, relating to (i) decision-making tools in sustainability assessment, based on the description of sustainability assessment tools in (St Flour and Bokhoree, 2021), (ii) decision-making, and (iii) stormwater management, based on various concepts which have been developed and used worldwide for sustainable SWM practices. Delimitations were made to the assessment scale of sector-based and project-based tools only. The following search strings were applied in conjunction with each other:

- **Sustainability assessment decision-making tools:** "multi-criteria decision analysis" OR "multi-criteria decision making" OR "multi-criteria analysis" OR "Dow Jones Sustainability Index" OR "Environmental Impact Assessment" OR "Strategic Environment Assessment" OR "Composite Sustainable Development Index" OR "Full Cost Accounting" OR "Integrated Value Model for Sustainable Assessment" OR "Cost-Benefit Analysis" OR "System Dynamics" OR "Sustainability Assessment Model" OR "Sustainability Assessment by Fuzzy Evaluation" OR "Fuzzy Logic Approach for Sustainability Assessment based on the integrative Sustainability Triangle" OR "Adaptive Neuro-Fuzzy Inference System";
- **Decision-making:** "decision making" OR "decision support" OR "policy" OR "policy making".

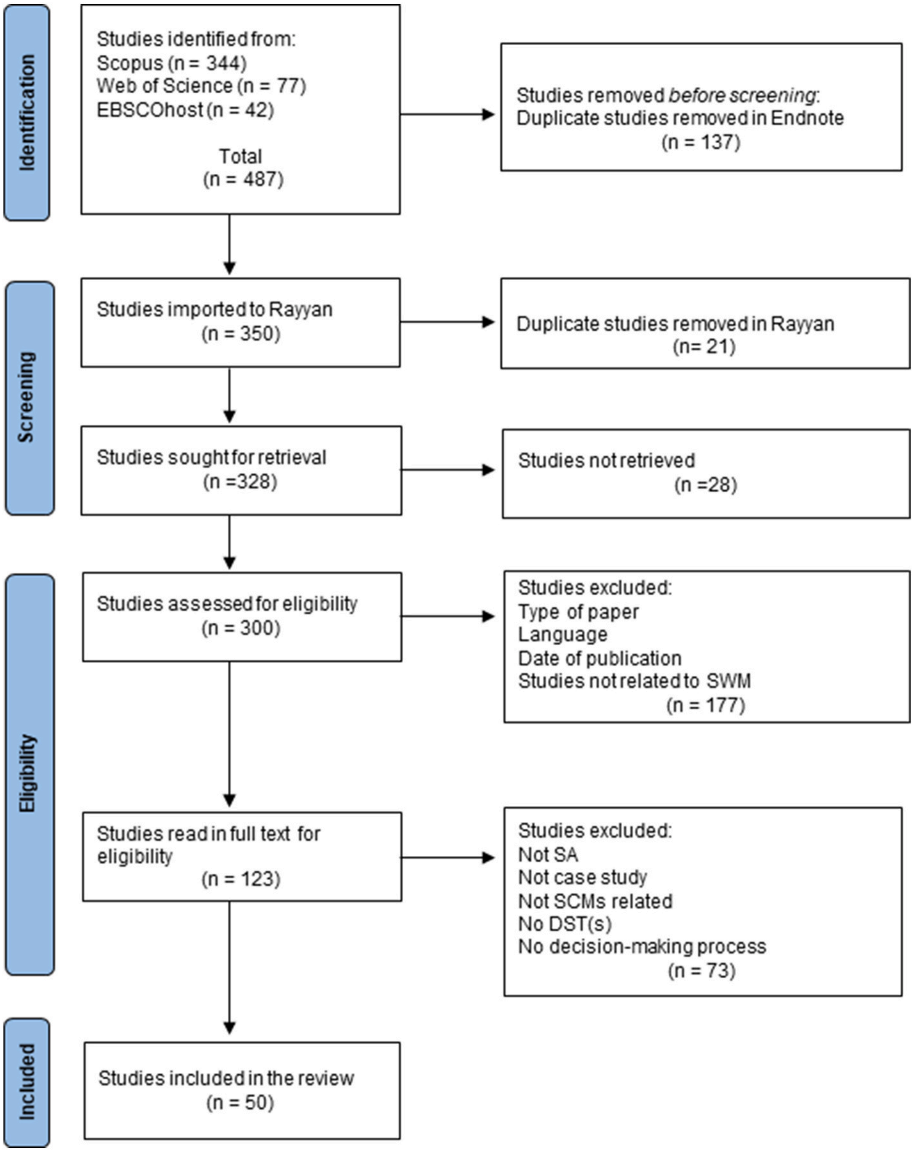

**Fig. 1.** Flow diagram of the selection process based on PRISMA (Page et al., 2021).

- **Stormwater management:** "stormwater management" OR "low impact development" OR "sustainable urban drainage system" OR "best management practice" OR "water sensitive urban design" OR "nature-based solution" OR "green infrastructure" OR "stormwater control measure*" OR "Sponge City".

The search was conducted in October 2022 and resulted in a total of 487 papers. From these, duplicates, irrelevant papers (based in reading abstract and titles), papers inaccessible in full-text, non-original research papers, papers not in English language, papers not published in peer-reviewed journals (*i.e.,* no conference proceedings, book chapters, technical reports, and government documents) were excluded, resulting in a total number of 123 papers published between 2010 and 2022. These were included in the full-text reading and skimmed through for eligibility in line with the objective of this review. Based on this, another 73 papers were excluded and, thus, a total of 50 papers were comprised as the final sample of this review.

In order to analyze the selected papers, we applied the Policy Arrangement Model to our analysis (Arts et al., 2006). The model is a conceptual framework, developed in environmental policy studies to assist understanding stability of content and organization of a policy domain. Arts et al. (2006) defines a policy arrangement as the state in which the interaction between political actors and resources and rules of the game solidifies in a temporary stable structure (institutionalization), before the driving force of evolution forces them to readjust their interdependency. The model comprises four profoundly interconnected dimensions: actors, resources, rules of the game, and discourses. Each of these dimensions affects the others and changes the shape of the entity, such as new actors' appearance may lead to division of resources, new rules of the game and/or new discourses. Previous reviews related to SWM and urban forest management have used policy arrangement model as an analytical framework (Ordóñez et al., 2019; Qiao et al., 2018)

For clarity, we used the following definitions for the review:

**Discourse**: represents the "pre-defined" problems and the intentions behind the SWM approach. In this review, *discourse* may resonate with the research questions and terminology used in the articles to communicate ideas and concepts related to sustainable SWM.

**Rule(s) of the game:** refers to both legally and non-legally binding documents, reports, guidelines, standards, *etc.*, which may require the use of specific DSTs, or have an influence on the decision-making process in the context of sustainability assessment for SWM.

**Actors:** stand for both stakeholders who have a direct interest and are actively involved in the decision-making process, as well as those who are indirectly affected and may be distantly addressed. It includes proponents, decision agencies and end users from both public (governmental) to private (consultants and community) domains.

**Resources:** denote knowledge, finance, data, time input, *etc.,* influencing the selection and utilization of DSTs.

## 3. Results

### *3.1. Geographical and research context*

The reviewed studies encompass a variety of 19 countries (Fig. 2a) with a dominant number of studies in North America, Europe, China, and Australia (Fig. 2b). Most of the articles included in the review are based on studies in Europe (n = 16), North America (n = 14), China (n = 10) and Australia (n = 6). This global distribution corresponds to the widespread acceptance and application of sustainable SWM concepts, regions with a high study representation, in particular, are frequently at the forefront of introducing novel concepts to stormwater management. While early studies from Europe and the North America were based on the concepts such as Sustainable Urban Drainage Systems, Best Management Practices (a term less commonly used today and being replaced by *e.g.,* NbS), and Low Impact Development (with stormwater control measures). In recent years, there has been a notable global rise in the adoption of these systems and concepts, specifically, Australia has shown a specific interest in Water-Sensitive Urban Design, while China has emphasized Sponge Cities, as discussed in detail by Fletcher et al. (2015). The specific focal points and driving factors vary due to the diversity of local, regional, and national challenges, including but not limited to climate change adaptation, reduction of combined sewer overflows, improvement of bathing and receiving water quality, and the necessity of rainwater harvesting due to drought. Nonetheless, amidst these variations, there exists an overlap in these concepts and technologies.

Overall results also indicate how the research area of DST in SWM as finally included in this review has increased between 2010 and 2022 (Fig. 2c), and how most research papers have economical (n = 45) and environmental (n = 42) sustainability criteria being included, compared to social (n = 26) and technological criteria (n = 28) (Fig. 2d). The emphasis on technical-environmental criteria revealed the predominant consideration in these countries/regions. Technical-environmental needs (retention and water quality treatment) have long been the main drivers for the implementation of stormwater control measures (Butler et al., 2018). When including ecosystem services, SWM moves from being a technical water management issue to a multidisciplinary issue involving a broader spectrum of actors and requiring other economic considerations (Darnthamrongkul and Mozingo, 2021). Issues to be regarded besides the technical function are *e.g.* public and societal perception and multiple economic beneficiaries of sustainable SWM. Still, the relatively lower representation of social and technological criteria in current DSTs shows potential for further investigation and development, particularly in terms of combined social and technological advancements in SWM.

We also found a steady increase in the number of publications over the last 10 years, with a peak of 12 publications in 2020. The years 2016 and 2022 were also notable with 8 and 10 publications respectively. These findings suggest that the research topic of using DSTs as part of sustainability assessment in SWM has gained increasing interest in recent years. With regards to sustainability criteria, economic and environmental concerns scored the highest interest (n = 45 and 42 respectively) compared to the technological and social domains (n = 28 and 26). These findings suggest that social and technological sustainability may not be given as much emphasis in the DST's assessment of SWM strategies compared to economic and environmental sustainability.

### *3.2. Application of DSTs in SWM*

In response to objective 1, in total 11 DSTs were identified in the

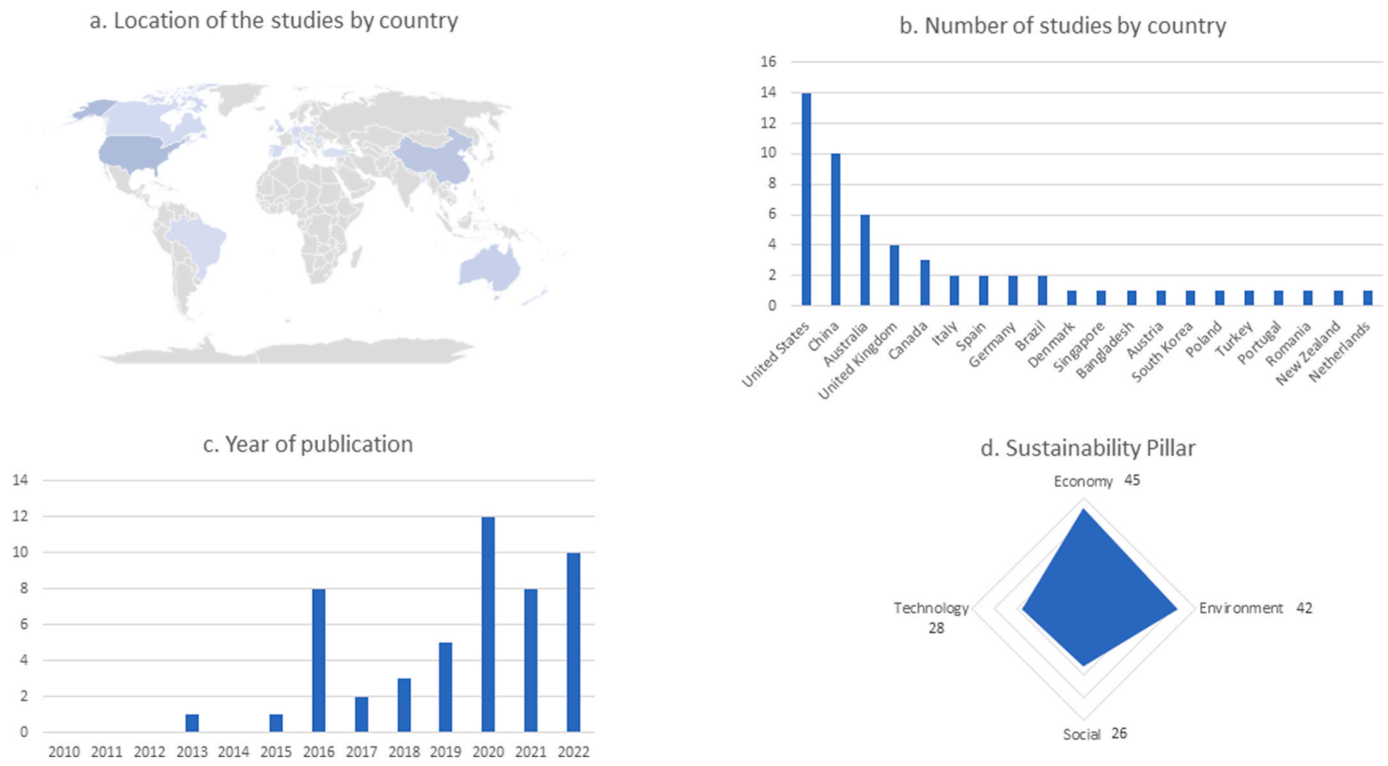

**Fig. 2.** a) Location by country of the reviewed studies; b) the number of the published studies by country; c) timeline of studies in review based on year of publication; d) identified sustainability assessment pillars in the published studies.

sustainability assessment of SWM (Table 1), of which 16 % (n = 9) out of the 50 papers used integrated DSTs. Instead of simply counting the number of instances, we counted the occurrences of different DSTs used in the research papers. The most used DST applied both as a separate approach and in combination with other tools, was Multi-Criteria Analysis (MCA), which appeared in 26 of all reviewed papers. Cost-Benefit Analysis (CBA) was the second most frequently used tool (n = 11), followed by Life Cycle Costing (LCC) (n = 7), Life Cycle Assessment (LCA), and System Dynamics (SD) (n = 3 each), Cost-Effectiveness Analysis (CEA) (n = 2), and finally the remaining DSTs were only used once each (n = 1). Table 1 presented a general description of these tools and their applications in the reviewed studies. The disparity in the usage of DSTs reflects the complex nature of sustainability assessments. Notably, the prevalent use of MCA suggests its suitability for multifaceted assessment demands. This predominance is attributed to its flexibility with various techniques (Luan et al., 2019), its capacity to integrate complex quantitative and qualitative data (Axelsson et al., 2021), and its applicability to handle multiple, often conflicting, criteria in a consistent manner (Liquete et al., 2016). Conversely, tools with fewer occurrences may be associated with their highly novel, specialized, and complex application. For instance, Rapid Decision Support Tool use unique Ecosystem Services variables for the SWM retrofitting purpose (Scholz and Uzomah, 2013), Agent-based Model excels in simulating the actions and interactions of agents to assess their collective impact on the system (Castonguay et al., 2018), and Long-Term Hydrologic Impact Assessment can leverage detailed land and climate data to estimate long-term effectives and payback time (Wright et al., 2016). However, in contrast to MCA's broad applicability, these tools often target highly specialized domains and require significant computational resources, or they might be seen as innovative and novel, lacking in accessible datasets. These may confine their application to a smaller community of SWM sustainability assessment specialists. Nonetheless, accelerating advancements in computational power and artificial intelligence technologies could broaden the accessibility and applicability of some of these tools in the future (Dwivedi et al., 2021).

Despite the diversity of DSTs available for specialized applications in SWM sustainability assessment, these tools were utilized to assess various design variations within the same stormwater control measure, such as different types of rain barrels. Additionally, 49 % were used to compare different stand-alone stormwater control measures to each other, *e.g.*, assessing the performance of green roofs versus rain gardens. Furthermore, 51% of the tools were utilized to assess the combined performance of multiple stormwater control measures, such as integrated constructed wetlands, sedimentation ponds, and rain gardens as a combined system to another alternative within the same catchment scale. By linking the records of the DST and its usage, the result indicates the capacity of each DST towards the modes of the stormwater control measures.

### *3.3. Application of DST in stormwater governance and management*

#### *3.3.1. Discourses*

The primary discourse related to the use of DST was towards water quantity control *(i.e.*, managing the volume and velocity of stormwater runoff) and represented in 34 % (n = 17) of the papers, 24 % (n = 12) were related to water quality interests (*i.e.,* the reduction of pollutants and contaminants), and 42 % (n = 21) were addressing both, as mutual concerns. This latter approach indicates that some DSTs (*e.g.,* MCA, SD, CBA) can assist in developing effective solutions for interrelated issues, which is needed in practice when *e.g.,* multifunctionality is desired (Castro, 2022; Ebrahimian and Wadzuk, 2022; Koc et al., 2021; Liang et al., 2020; Luan et al., 2019; Oladunjoye et al., 2022; Xiong et al., 2020). The combined approach to sustainable SWM also resonates with how the DSTs are used to assess individual measures (*i.e.,* separate installations of swales, bio-retention ponds, *etc.*) or combined measures (*i.e.*, a system approach with several combined installations), and how the comparison between alternatives are possible, either between individual measures, combined measures, or both. Additionally, some studies have explored the optimal scenarios for SWM by comparing individual stormwater control measure with combined measures (Kaykhosravi et al., 2022), and some studies have explored implementing scenarios across multiple scales (Dong et al., 2020), and even the feasibility of multi-site implementations (Locatelli et al., 2020).

Furthermore, as presented in Table 2, the objectives of the reviewed articles indicated that 47% (n = 29) focused on the performance of stormwater control measures, 34% (n = 21) discussed the benefits and values of SWM, and 18% (n = 11) evaluated overall strategies and policies.

#### *3.3.2. Actors*

Understanding who the actors are, and their roles, is crucial for examining the governance and management aspects in the application of DSTs, especially with concern to potential conflicts of interest (Barton et al., 2020). By categorizing actors based on their roles and responsibilities, we can better understand their likely contributions (interests) to the SWM decision-making process (McIntosh et al., 2011). Some actors may fit into more than one category depending on their roles and mentioned responsibilities. Governmental or municipality officials represent the most occurring category of actors by 43% (n = 23), followed by the utility sector, 20 % (n = 10), and experts, 12 % (n = 6). The least representative actors were local community stakeholders, 8 % (n = 4), property owners, 4 % (n = 2), and actors from industry banks and insurance companies, 2 % (n = 1).

#### *3.3.3. Resources*

Resources play a significant role in the decision-making process, for instance, via access to knowledge and data, *etc*. This was recognized as the paramount resource in the decision-making process when utilizing the DSTs with 48 % (n = 24) including 5 papers specifically addressing local knowledge and expertise as valuable and 4 studies relating to expertise and scientific judgment. Time was addressed in 4 papers, and financial resources, as in the budget allocated to the project, were only mentioned in 2 papers. Also, the DSTs themselves can be regarded as a resource, based on their ability to support and define other resources needed in the decision context.

#### *3.3.4. Rules of the game*

A number of papers (n = 46) were found to employ the rules of the game in their research on applying the DSTs. These rules primarily consisted of non-legally binding documents (n = 44), including agendas, reports, guidelines, and standards from international to local levels. Only 3 articles specifically referred to the legally binding regulation, and a small subset of articles (n = 5) drew upon additional rules from projects as the primary setting. These legally or non-legally binding rules played a pivotal role in various aspects of the decision-making process for sustainability assessment, as they provided a basis for defining SWM problems, and setting motivations, rationales, and objectives for the SWM assessment. Additionally, they guided the establishment of sustainable SWM requirements, alternatives, functions, and benefits, as well as the determination of criteria for sustainability assessment. Furthermore, these rules were instrumental in identifying DSTs, as well as in conducting scenario analysis, which allowed for the assessment of various sustainable SWM strategies through modelling and simulation processes.

## 4. Discussion

Policy arrangement model as the analytical framework in our review, is not an ontological description of reality, but an analytical and heuristic framework to articulate governance and management. In the following discussion, we deliberate on our findings from the objectives that have framed this review.

**Table 1**
Identified DSTs with summarized descriptions and techniques in sustainable assessment of SWM case studies, illustrating the application modes - Individual (I) stormwater control measure or Combined (C) stormwater control measures.

| DST | Description | Techniques | Individual (I) or Combined (C) | Occurrences |
|---|---|---|---|---|
| Multi-Criteria Analysis (MCA) | MCA is a family of methods that enables the evaluation of alternatives based on multiple criteria. It utilizes various approaches and techniques to assess different SWM practices and stormwater control measures within the various frameworks, while also being able to engage stakeholders and decision-makers. | - Analytic hierarchy process<br>- Fuzzy-based approach<br>- Technique for order of preference by similarity to ideal solution<br>- Preference ranking organization method for enrichment evaluations<br>- Optimization approaches<br>- Shapley choquet aggregation<br>- Delphi method<br>- Scoring (Likert scale)<br>- Parameter ESTimation<br>- Multi-attribute value<br>- Bayesian belief networks | I or C | 26 |
| Cost-Benefit Analysis (CBA) | CBA is a tool used to evaluate the costs and benefits associated with different SWM strategies. It is a valuable tool for decision-makers to determine the most cost-effective solution while considering multiple objectives, such as monetized environmental and social benefits. It can help to identify the best management practices that deliver the greatest benefits and maximize the return on investment. | - Benefits Estimation Tool (B£ST)<br>- I-DST<br>- Net present value<br>- Average service life span<br>- The economics of ecosystems and biodiversity<br>- Benefit cost ratio<br>- System for urban stormwater treatment and analysis integration<br>- Willingness to pay<br>- Investment framework for economics of water sensitive cities | I or C | 11 |
| Life Cycle Cost (LCC) | LCC can evaluate the cost of stormwater control measures over its entire life cycle, including initial capital costs, maintenance costs, and end-of-life disposal costs. It can help decision-makers compare the cost-effectiveness of different SWM strategies and identify the most cost-effective option. | - Net present value<br>- Benefit cost ratio<br>- Internal rate of return | I or C | 7 |
| Life Cycle Analysis (LCA) | LCA can be used to assess the environmental impacts of a stormwater control measure over its entire life cycle. It can provide value to compare different design options and identify areas for improvement in terms of reducing the measure's environmental impact. | - International Organization for Standardization (ISO) protocols.<br>- Cumulative energy demand<br>- Carbon footprint<br>- ReCiPe midpoint hierarchist | I | 3 |
| System Dynamic (SD) | SD is a modelling tool used to understand the behavior of complex systems over time, such as combined stormwater control measures. It supports evaluating long-term performance, predicting future impacts, and developing adaptive strategies that are resilient to changes. | - Casual loop diagram<br>- Fuzzy cognitive mapping<br>- Participatory modeling | C | 3 |
| Cost-Effectiveness Analysis (CEA) | CEA is a tool or sometimes a technique for LCC that is used to compare the costs of different strategies in SWM that achieve similar outcomes. It assists decision-makers to identify the most efficient and cost-effective solution, such as reducing stormwater runoff or improving water quality. | - Monte Carlo simulation<br>- System for urban stormwater treatment and analysis integration<br>- Benefit cost ratio<br>- Cost effectiveness ratio | I or C | 2 |
| Rapid decision support method (RDSM) | RDSM is a structured and participatory decision-making approach that helps to identify and evaluate alternative solutions to complex problems promptly. It is based on the Ecosystem Services' variables. | - Ecosystem Services' variables | I | 1 |
| Agent-Based Model (ABM) | ABM is a tool that models the behavior of individual agents and their interactions in a complex system. It is commonly used to study complex social, economic, and ecological systems and to explore the impacts of different policies and interventions. | - UrbanBEATS & DynaMind | C | 1 |
| Green pass Toolbox | Greenpass Toolbox is a web-based platform that supports decision-making in the management of green infrastructure, such as urban parks, green roofs, and wetlands. It provides tools and data for planning, designing, and assessing the performance of green infrastructure projects. | - GIS with Simulation & Evaluation System | C | 1 |
| Long-Term Hydrologic Impact Assessment (L-THIA) | L-THIA is a model that estimates the long-term hydrologic impacts of land use changes on a watershed. It can be used to assess the impacts of urbanization, agricultural practices, and other land use changes on water quality and quantity. | - Modeling with curve number method | I | 1 |
| Strengths, Weaknesses, Opportunities, and Threats (SWOT) | SWOT is a framework for assessing the internal and external factors that affect the performance of an organization or project in strategic planning and management to identify potential risks and opportunities | - Analytic hierarchy process | I | 1 |

**Table 2**
Summarized main objectives of reviewed articles related to SWM.

| | Themes | Objective | Occurrences |
|---|---|---|---|
| Discourse | performance of stormwater control measures | Functions & configuration; combination mode; spatial layout; spatial scale; and spatial distribution | 29 |
| | Benefits and Values | Direct or indirect benefits trade-off & synergies | 21 |
| | SWM Strategies | Policies; regulations; and schemes/scenarios | 11 |

### 4.1. *What SWM themes are DSTs applied for?*

To address objective 2 of this study, we identified three major themes relating to the discourses throughout the reviewed papers: (i) performance of stormwater control measures, (ii) benefits and values, and (iii) SWM strategies (Table 2).

#### 4.1.1. *Performance of stormwater control measures*

The performance of stormwater control measures, including retention, purification, infiltration, storage and reuse, evapotranspiration and heat absorption, provision, and improvement of habitat and green spaces, *etc.* was the most mentioned objective, ranging from grey infrastructure to green infrastructure based on their technical function and configurations to control and management of stormwater, including measures of *e.g.*, bio-retention, rain gardens, permeable pavement, and green roofs. The efficiency of the measures is reflected in the optimal performance of the proposed measure. Moreover, the objective of some studies was to use DSTs to find the combination of spatial location, scale, and distribution for implementation. Instead of focusing on the functions, these studies also used DSTs to investigate the baseline alternatives of the measures based on either centralized or decentralized approaches, the spatial layout (*e.g.*, source control, process control, end control), and the size of the catchment area. Two studies included both aspects and used DSTs to assess the optimization of different measures based on the functions and configuration, combination mode, and spatial distribution (spatial scale and size).

#### 4.1.2. *Benefits & values*

Benefits and values were the second most addressed SWM theme of the reviewed articles, and could, in turn, be identified as either direct benefits (*e.g.*, reduced runoff, improved water quality, water restoration, groundwater recharge, improved water supply, protection of green space, reduced temperature, and reduced greenhouse gas emissions) or indirect benefits (*e.g.*, enhanced aesthetics, improved public health, flood mitigation, biodiversity conservation, human well-being, education, and urban heat island reduction).

#### 4.1.3. *SWM strategies*

Several studies also sought to evaluate the effectiveness of the overall management approach or top-down stormwater policy, rather than specifically examining the implementation of stormwater control measures or their associated benefits. These studies typically focused on evaluating schemes, scenarios, and policies derived from the functions of stormwater control measures, and comparing different strategy alternatives to identify the long-term pathway that best aligns with their contextualized sustainability in SWM (*e.g.*, addressing the impacts of climate change or urbanization).

### 4.2. *How do DSTs support stormwater governance and management aspects*

#### 4.2.1. *Rules*

In this review, most studies demonstrate a reliance on non-legally binding rules that are specific to the context, which allows for flexibility and adaptation to geographic contexts and evolving knowledge. In addition, it enables proponents to incorporate local pertinent indicators into SWM assessment (Halla et al., 2022). As emphasized by Hartmuth et al. (2008), sustainability assessment must be customized to the specific characteristics of the local context. Despite the instrumental role of these rules in establishing the local pertinence for DSTs in SWM assessment, the limited utilization of legally binding rules can pose a potential barrier to achieving consistent and standardized sustainability assessment approaches to sustainable SWM across different contexts. Further, the absence of legislation in sustainability assessment may impede the acceptance and support of sustainable SWM strategies by stakeholders (Castro, 2022).

#### 4.2.2. *Resources*

As aforementioned, under the resources dimension of policy arrangement model, the DST could consider or be affected by a range of identified resource factors, such as the financial resources available for implementing SWM strategies, the availability of human resources to support, design, and implement the strategies, the accessibility of appropriate data and time needed to evaluate the stormwater control measures, and the availability of land for stormwater control measures (Qiao et al., 2018). However, financial resources and budget allocation were only mentioned in 2 studies (Castonguay et al., 2018; Ebrahimian and Wadzuk, 2022). Therefore, and in line with Mullins et al. (2023), we view DSTs themselves as a resource that supports the execution of the decision objectives, *e.g.*, as supporting data acquisition, insights, knowledge, expertise, financial resources, time, *etc*. CBA, CEA, and LCC can be attributed to the availability of accessible monetized resources and policy incentives, and this influence of financial considerations is reflected in the choice of DSTs. However, some researchers have argued that proponents tend to use these tools to simplify SWM decision strategies, rather than taking a holistic approach. Holz et al. (2004) and Furlong et al. (2017) have highlighted the potential drawbacks of over-reliance on monetization-based DSTs, as this dependency may oversimplify the decision-making process by structuring complex issues to a single criterion. Similar arguments were raised by Scerri and James (2010) who claimed that sacrifices made, *e.g.*, environmental or social aspects to achieve improvements in economic aspects, will lead to prioritization of economic development at the expense of the other aspects of sustainability.

With respect to addressing this drawback, the integration of more than one technique in the decision-making process is observed, such as combining Analytic Hierarchy Process technique to develop weights of criteria and Technique for Order of Preference by Similarity to Ideal Solution technique to test stormwater policy alternatives in MCA (Axelsson et al., 2021; Koc et al., 2021). Similarly, as presented in Table 3., some studies applied one DST as an auxiliary to another, such as using CBA as supplementary to MCA to provide a more comprehensive assessment by incorporating both monetary and intangible criteria (Rizzo et al., 2021; Teotónio et al., 2022), likewise, utilizing MCA as auxiliary to SD to enhance the understanding of complex and dynamic systems, allowing for a more accurate representation of the real-world scenarios (Xi and Poh, 2015).

#### 4.2.3. *Actors*

Sustainability assessment of SWM is a complex process that includes multiple actors, *e.g.*, state government, water utility, developers, civil society actors, and households, although different DST of sustainability assessment studies conceptualize the roles of actors in different ways, from the reviewed studies, we have discerned the following distinctive roles:

*Proponents* are typically the researchers who undertake the sustainability assessment (Pope and Grace, 2006) and develop, apply, or demonstrate the DSTs, which are designed to investigate various issues of sustainable SWM and to propose resolutions either with (engaged) or without (distance) other actors. They play a critical role in advancing

**Table 3**
Integrated DSTs and framework.

| Integrated DSTs | Details and rationales | Reference |
|---|---|---|
| LCA & SD | Integrated LCA & SD in assessing and evaluating different nutrient treatment efficiencies under various spatial and temporal settings, this dynamic framework can be generalized to different environmental and system conditions to inform the future design and optimization of green infrastructures applications | Bixler et al. (2019) |
| MCA & LCC | LCA as auxiliary to many-objective optimization approaches[a], allowed stormwater best management practices to be evaluated by stakeholders before the portfolio selection process.<br>MCA for assessing alternative solutions on hydro benefits was incorporated with LCC, with regard to enhancing planning-level analyses by expanding information for decision-makers. | Di Matteo et al. (2019)<br>Gallo et al. (2022) |
| LCC & CBA | LCC and CBA as the integrated DST were utilized due to the quantitative and comparative purpose for the assessment of green infrastructure performance.<br>Monetized climate impacts by LCC and community rainwater harvesting benefits with CBA to propose a community rainwater harvesting system as an alternative water supply solution for supporting policy decision-making. | Heidari et al. (2022)<br>Islam et al. (2021) |
| LCA & LCC | Integrated LCA and LCC models were used to evaluate the cost and environmental impacts of permeable highway pavements. | Hung et al. (2021) |
| MCA & CBA | MCA to compare grey and green infrastructure alternatives for the management of a combined sewer overflow, in which the criteria related to ESS were monetized with an adjusted value transfer (VT) method (B£ST software)[b].<br>Developed Modelling of the attractiveness of Green Infrastructure through a combined approach (MAGIGA) with MCA and CBA for assessing the value of green roofs and walls, so as to overcome the limitation of CBA. | Rizzo et al. (2021)<br>Teotónio et al. (2022) |
| MCA & SD | Synergized SD with MCA to compare different alternatives based on performance as revealed by the SD simulation and the judgment of decision makers. | Xi and Poh (2015) |

[a] multi-objective assessment is a type of multi-criteria analysis (MCA).
[b] Value transfer (VT) method such as Benefits Estimation and Screening Tool (B£ST) is considered part of the CBA family.

knowledge in the field of SWM that can support decision-makers to make more informed and sustainable choices (Gibson et al., 2005).

*Decision agency* comprises the actors who have the power or are empowered by the proponents to make decisions and are directly involved in the decision-making process (Gorddard et al., 2016). They are responsible for developing strategies related to SWM, as well as implementing stormwater control measures and weighing the benefits in a decision-making process (leBrasseur, 2022). Decision agencies play a key role in determining the trade-offs in the sustainability of SWM practices and solutions. In this review, these actors include government agencies, authorities, utilities, property owners, and decision-makers.

*End users* include actors who may not have a direct role or stake in the decision-making process but are impacted by SWM outcomes (McIntosh et al., 2011). These actors were observed in this review as commerce, contractors, bank and insurance industry, public/citizens, and residences/community. End users can provide feedback and input on SWM decisions, as well as influence outcomes through their actions. For example, the bank and insurance industry can influence implementation of stormwater control measures through their lending and insurance practices (Kordana-Obuch and Starzec, 2020), while residents and community groups can promote sustainable stormwater practices through advocacy and education campaigns in developing and implementing SWM plans and strategies (Kaykhosravi et al., 2022).

All in all, the nature of sustainability assessment in SWM is not only a technical appraisal approach providing direct input for decision-making, but also a possible approach for supporting governance, which involves communication and knowledge dissemination among the actors with different roles that are deployed in sustainability assessment decision contexts (Bond and Pope, 2012; van Zeijl-Rozema et al., 2008). The density and openness of the decision context in sustainability assessment of SWM consider the actors (proponents and decision agency) that establish the decision process, including the interconnected systems of values, rules, and knowledge that determine how the decision process is framed (Gorddard et al., 2016). In this regard, the plurality of actors addressed in the decision-making process from the review studies can serve as a basis to resonate what van Zeijl-Rozema et al. (2008) called *'deliberative governance'*.

However, despite the recognized importance of actor engagement in decision-making processes, most studies have only superficially addressed actors by simply stating that the decision outcome would benefit them. Only a handful of studies had comprehensively presented the process of engagement, and just one study had the recorded uptake of the decision result by the water utility (Rizzo et al., 2021). As stated by Giordano et al. (2021), stakeholders' engagement has a crucial role to support understanding and valuing the differences among individual co-benefits. Nonetheless, this also presents a dilemma regarding *when* and *where,* and *how* actor engagement will ensure the uptake of the decision-making, not to mention the quality, quantity, and appropriateness of their involvement in the actual decision-making processes (McIntosh et al., 2011). Furthermore, actors involved in Sustainable SWM have diverse interests and competing agendas, which have a significant impact on policy goals and influence trade-offs between short and long-term objectives, as well as the hydrological processes integral to SWM practices (Dhakal and Chevalier, 2016; Henstra et al., 2020). This complex interaction of diverse interests and conflicts among stakeholders shapes decision-making processes and outcomes. In this review, only one study was found to specifically address conflict per se, with a focus on the assessment of the stormwater control measures response to different policy conflicts (Castro, 2022). Therefore, future research should highlight the research gap of actor engagement and their multifaceted interests and conflicts in the application of DSTs, in order to ensure optimal decision-making outcomes and facilitate effective deliberative governance.

### *4.3. How can future DST best include governance and management aspects?*

Understanding governance dimensions such as discourses, rules of the game, actors, and resources (Arts et al., 2006), and integrating them into the sustainability assessment of SWM would significantly enhance the decision-making context. This, in turn, facilitates the selection of suitable DSTs and the effective alignment of their distinct strengths. For instance, the capacities of MCA in considering intangible criteria and trade-offs among actors emphasize its potential in including governance-oriented elements inherently. Conversely, tools such as CBA and LCC, with their specific focuses on assessing economic feasibility and temporal impacts, respectively, offer valuable insights into management-oriented concerns such as landscape design, maintenance, and planning.

However, solely focusing on the capacity of the DST or how to apply DST is not sufficient. After all, the fundamental input criteria remain crucial, regardless of the DST applied, it is necessary to utilize sustainability criteria to determine whether the stormwater control measures or strategy is likely to contribute to the set objectives (Foxon et al., 2002). Of the 50 reviewed papers, 49 papers utilized DST to assess at least two pillars of sustainability, with economy and environment being the most frequently assessed. Relatively fewer articles assessed the social aspect, with only 17 articles covering all pillars of sustainability, this demonstrates that there is still a gap in DST in assessing all pillars of sustainability. To ensure a comprehensive and robust assessment of sustainability objectives in sustainable SWM, it is essential to incorporate all pillars of sustainability, as emphasized by several studies (Foxon et al., 2002; Hugé et al., 2013; Pope et al., 2017).

It was observed that social criteria were not adequately addressed in most of the articles. Specifically, only 26 articles included social criteria, as presented in Table 4. Health and recreation are the most predominant indicator of the social criteria, followed by aesthetics, accessibility, and green economy. However, most of the papers only mentioned the concepts by name and did not elaborate on how and in which context in the decision-making process these intangible criteria were applied. We also observed inconsistency in some of the papers regarding how social criteria was addressed, *e.g.*, air pollution removal as the social criterion in Yao et al. (2022) and as the environmental criterion in leBrasseur (2022). Similar inconsistency was noticed in the categorization of water quality improvement, where Johnson and Johnson and Geisendorf (2019) addressed this as a social criterion and Liquete et al. (2016) as environmental. Nevertheless, the legitimacy, credibility, salience, and feasibility of the indicators are the keys to open and informed deliberations (van Oudenhoven et al., 2018). By incorporating social criteria in the sustainable assessment of SWM, open and informed deliberations can be encouraged to enhance the capacity, motivation, and habitual inclination of private actors and end-users toward sustainable decision-making. Moreover, the fostering of reciprocal awareness and collective responsibility can further promote long-term sustainability (Gibson, 2001, 2006).

**Table 4**
Of all 50 papers, a total of 26 specifically addressed aspects of social sustainability as a part of the DST. Identified benefits and values either as indicators or criteria under the social pillar of different sustainability assessment frameworks are outlined in this table.

| Social value & benefits | Numbers of instances | Reference |
|---|---|---|
| Environmental justice and green space accessibility | 10 | Axelsson et al. (2021); Coletta et al. (2021); Ebrahimian and Wadzuk (2022); Johnson and Geisendorf (2019); Kaykhosravi et al. (2022); leBrasseur (2022); Scharf et al. (2021); Teotónio et al. (2022); Xiong et al. (2020) |
| Civic engagement (the public/local community) | 9 | Axelsson et al. (2021); Brudermann and Sangkakool (2017); Coletta et al. (2021); Di Matteo et al. (2019); Iftekhar and Pannell (2022); Koc et al. (2021); Liquete et al. (2016); Oladunjoye et al. (2022); Shojaeizadeh et al. (2019) |
| Education | 6 | Ebrahimian and Wadzuk (2022); Kaykhosravi et al. (2022); Langemeyer et al. (2020); leBrasseur (2022); Oladunjoye et al. (2022); Rizzo et al. (2021) |
| Green economy (new enterprising) | 4 | Koc et al. (2021); Liquete et al. (2016); Teotónio et al. (2022); Xiong et al. (2020) |
| Health & recreation | 16 | Axelsson et al. (2021); Brudermann and Sangkakool (2017); Castro (2022); Di Matteo et al. (2019); Ebrahimian and Wadzuk (2022); Iftekhar and Pannell (2022); Johnson and Geisendorf (2019); Kaykhosravi et al. (2022); Langemeyer et al. (2020); leBrasseur (2022); Liquete et al. (2016); Oladunjoye et al. (2022); Rizzo et al. (2021); Scharf et al. (2021); Xiong et al. (2020); Yang and Zhang (2021) |
| Aesthetics | 11 | Brudermann and Sangkakool (2017); Ebrahimian and Wadzuk (2022); Iftekhar and Pannell (2022); Johnson and Geisendorf (2019); Kaykhosravi et al. (2022); Koc et al. (2021); Kordana-Obuch and Starzec (2020); Langemeyer et al. (2020); leBrasseur (2022); Oladunjoye et al. (2022); Shojaeizadeh et al. (2019); Teotónio et al. (2022) |
| Tourism | 2 | Scholz and Uzomah (2013); Oladunjoye et al. (2022) |

Future studies in sustainability assessment of SWM should therefore establish principles for standardizing frameworks to ensure adequate and contextually correct inclusion of all sustainability criteria, especially the social criteria. This will allow the best practices to be replicated on multisite, enabling greater consistency in the deliberative governance of sustainable SWM.

### 4.3.1. *Long term management*

Long-term approaches in sustainable SWM are recognized as crucial to really gain sustainability over the live length of the facility (Gibson et al., 2005; Qiao et al., 2018). Failed facilities due to lacking maintenance are a common challenge, meaning wasted investments and involve a risk for negative public perception towards sustainable SWM (Blecken et al., 2017). In this respect, DSTs, as well as hydrological models in SWM planning, are well-equipped to allow for long-term perspectives. Several DSTs, such as LCA, SD, LCC, and CBA, are developed to make longitudinal assessments ranging from 10 years to 50 years (Bixler et al., 2020; Hengen et al., 2016; Krieger and Grubert, 2021) This, in turn, allows decision-makers to understand how a system will behave over time and to identify potential long-term consequences of different decisions, or to evaluate management strategies that relate to operations and maintenance costs, as well as the stormwater control measure technical functionality per se. In addition, hydrological models that are used as auxiliaries to the DST are also used to generate long-term simulations. Storm Water Management Models, for example, can be used to simulate the quantity and quality of stormwater runoff under long-term hydrological scenarios (Jayasooriya and Ng, 2014). Still, long-term viability and function of NbS require empirical evidence of trial and errors, where experience of ongoing maintenance work of *e.g.,* raingardens and bio-swales contribute to valuable knowledge. This means embedding such expertise into DSTs to aid landscape planning and management and help link design of storm water measures to the long-term maintenance.

Moreover, several studies have investigated the long-term effectiveness of SWM policies and strategies, particularly in response to the challenges posed by climate change and urbanization. In these studies, different strategy alternatives and scenarios were compared from a long-term perspective (Brudermann and Sangkakool, 2017; Iftekhar and Pannell, 2022; Melville-Shreeve et al., 2016; Song and Chung, 2017). However, it is noteworthy that these strategy-related studies in sustainable SWM primarily focus on evaluating schemes, scenarios, and policies based solely on the assessment of stormwater control measures' functions or benefits. In addition, they tend to compare different strategy alternatives to identify the long-term pathway that best aligns with their objectives or discourses. As a result, the effectiveness of these strategies, which are based solely on the functions of stormwater control measures or solely on assessing the economic benefits of specific them as part of a larger plan, is questionable.

When it comes to the use of nature, or natural features of stormwater control measures, *e.g.*, expressed as NbS, our review has not generated enough evidence to suggest how long-term perspectives can be incorporated into DSTs. It is a fact that nature takes time to develop and that the transition of applying NbS in sustainable SWM will take a long time to develop from establishment (small scale) to extensive distribution (Köhler et al., 2019). But although nature-based, many stormwater control measures need maintenance to ensure long-term functionality (Blecken et al., 2017). Therefore, long-term monitoring of sustainable SWM when using NbS is needed, but often underdeveloped (Al-Rubaei et al., 2016). Future studies should include ex-post assessment, which will provide more tangible examples of the accurate long-term practice, local communities assessment, and experience, to identify NbS data as well as conditions that have led to sufficient maintenance to secure the technological requirements of NbS (Blecken et al., 2017). Given that lack of studies including the long-term functionality, incorporating it into DSTs remains a challenge and justifies further research.

## 5. Conclusion and limitations

This review aims to bridge the gap between sustainability assessment, sustainable SWM, and governance and management by investigating the roles of DSTs in sustainability assessment. We have applied the policy arrangement model as a heuristic framework to identify how DST may include governance dimensions. Further, we have explored DST's potential in supporting future real-world governance and management of urban SWM. In doing so, our findings indicate that, while there is a consensus on the significance of involving actors in the sustainability assessment of SWM, most efforts are still directed toward the technical development of DSTs. Therefore, there is a need to develop and combine the technical development of the DST with social aspects to ensure optimal decision-making outcomes and uptake. Furthermore, tangible examples and data on the long-term functionality of stormwater control measures through ex-post assessments were underexplored, this encompasses understanding how to effectively incorporate them into DSTs. Overall, despite the reviewed DSTs being primarily ex-ante, we identified significant potential for these tools to serve as a facilitative medium in supporting stormwater governance and management practices. Moreover, our results highlight three key aspects crucial to improving the effectiveness of decision support tools within stormwater governance and management, namely:

(i) Exploring practical challenges in integrating all sustainability assessment pillars with consistent criteria into DSTs. This is crucial to determine the optimal use of all criteria in fostering open and informed stormwater governance and management.
(ii) Understanding how to engage diverse stormwater actors with future DST, to secure ownership and relevance.
(iii) Use of retrospective (ex-post) sustainability assessments *e.g.* as evaluations, are needed to provide more tangible knowledge and to support long-term management. This is particularly related to nature or natural aspects in sustainable SWM.

To our knowledge, this is the first study of a substantially interdisciplinary nature that systematically examines how governance aspects relate to prospective DSTs of sustainable SWM. We have utilized the policy arrangement model to examine associations among decision science, sustainability science, and natural science, and our results add to the rapidly expanding field of governance research in SWM, especially in sustainability assessment studies.

Regarding the limitation in this current review, the strength of the model as an analytical framework is at the same time its weakness. It contextualized the governance dimensions in the decision-making context and facilitated our understanding of the utilization of DST in the sustainability assessment. However, the model simplifies the complex understanding of the intricate policy-making processes that have dynamic actors' involvement. This makes it challenging to provide a comprehensive understanding of the broader governance structure surrounding SWM just by projecting from the ex-ante DSTs applied in academic research projects. Notwithstanding this limitation, continued efforts with grey literatures should be undertaken to explore how DST is applied in urban SWM practice. By bridging the gap between sustainability assessment, governance, and management in addressing real-world SWM challenges, we can acknowledge more potential of DSTs in future decision-making processes.

## CRediT authorship contribution statement

**Zhengdong Sun:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Johanna Deak Sjöman:** Writing – original draft, Methodology, Conceptualization. **Godecke-Tobias Blecken:** Writing – review & editing, Funding acquisition. **Thomas B. Randrup:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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